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RESONANCE CONTROL FOR A CW ACCELERATOR*

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Abstract

This paper describes a resonance-control technique that has been successfully applied to several cw accelerating structures built by the Los Alamos National Laboratory for the National Bureau of Standards and for the University of Illinois. The technique involves sensing the rf fields in an accelerating structure as well as the rf power feeding into the cavity and, then, using the measurement to control the resonant frequency of the structure by altering the temperature of the structure. The temperature of the structure is altered by adjusting the temperature of the circulating cooling water. The technique has been applied to continuous wave (cw) side-coupled cavities only but should have applications with most high-average-power accelerator structures. Some additional effort would be required for pulsed systems.

Introduction

A resonance-control technique has been successfully applied to several continuous wave (cw) accelerating structures built by the Los Alamos National Laboratory for the National Bureau of Standards (NBS)[1] and for the University of Illinois.[2] The technique is simple and novel and, to the best of our knowledge, has not been implemented previously, though no claim is made with regard to its originality. The technique involves sensing the rf field within an accelerating structure and using the measurement to adjust the resonant frequency by altering the temperature of the structure. The technique is presented in practical and analytical form, without developing the theory. To date, the technique has been applied to cw side-coupled cavities only but should have applications for most tuned cavities and, with additional effort, may be extensible to some pulsed-mode systems.

The purpose of the resonance-control technique was to develop a temperature regulation system for the NBS/Los Alamos Racetrack Microtron (RTM), an accelerator system consisting of several accelerating structures. A single rf generator is used to excite all the accelerating structures, by way of a variable power-splitter arrangement.[3] The result is that a change in the operating conditions of one cavity has an effect on all cavities. Amplitude-control loops are used to counteract these effects.

Description

Examining previous work in this area indicated that several different techniques have been used to regulate and match the resonant frequency of the cavity structure to the frequency of the rf source. Most of the structures have been temperature regulated; some have additional features such as mechanical tuners and/or variable frequency excitation. The techniques involve detecting a mismatch that has occurred and then taking corrective action. Temperature, reflected power, and voltage-standing-wave ratio (VSWR) have been used to detect mismatches. A resonance-regulation system that relies solely upon temperature regulation has difficulty in performing with a high degree of precision. The difficulties with this technique are (1) temperature is not the desired parameter, (2) the optimum location for the temperature sensing is generally not available, (3) the optimum location may not be constant for all operating modes, and (4) temperature sensors are generally not sufficiently sensitive.

The resonance-control system (see Fig. 1) functions over the full-power range of the structure from zero to maximum power. When the structure is not powered or operating at low power, the near-resonance condition is maintained with temperature regulation. When the structure operates at full power, the resonance condition is detected directly and is used as the process-control input. The process-control variable is the temperature of the circulating cooling water. The resonance condition is detected by measuring the phase shift between the rf drive and the cavity-field signal. When the rf frequency matches the structure's natural resonance frequency, the signals are in phase. The sign and magnitude of the phase difference, or error, are preserved in the off-resonance condition and, for small errors, is linear.

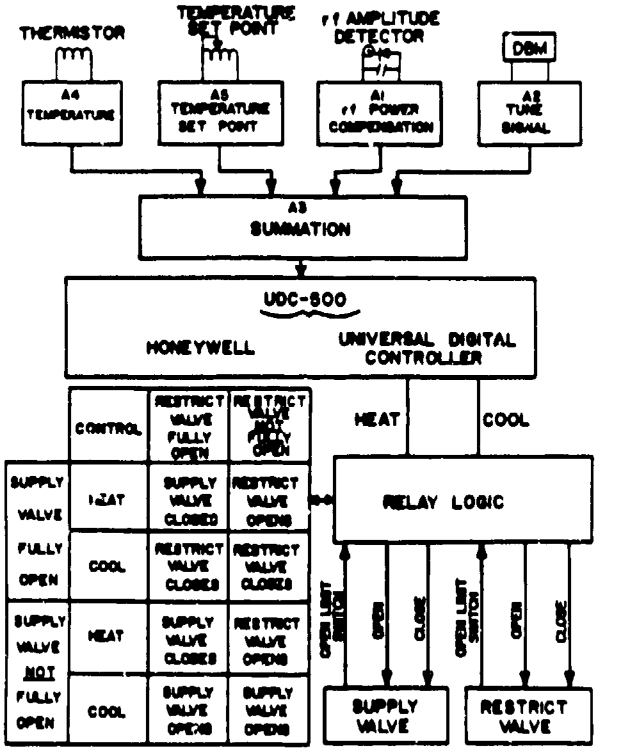

Fig. 1. A simplified diagram of the resonance-control system and the "truth table" for the relay logic that controls the supply and restrict valves.

The control algorithm is implemented with two overlapping control zones, each covering a limited range of power levels. The control algorithm is implemented with three separate control inputs. The control inputs are the temperature of the circulating water, the rf power in the structure, and the phase difference between the structure field and the rf drive. To achieve a smooth or bumpless transfer, the control inputs are combined in an adder circuit with different gains. Zone 1 covers the rf power from off to low rf power levels. Zone 2 dominates when the structure is operating from intermediate power levels to maximum power levels.

In Zone 1, the temperature of the circulating water is the dominant process-control input. The structures are designed to resonate naturally at the desired operating

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frequency at an above-ambient temperature. The structure must be heated in this condition. The structure is heated by closing the cooling-water supply valve, see Fig. 2, and allowing a 100% recirculation of the water

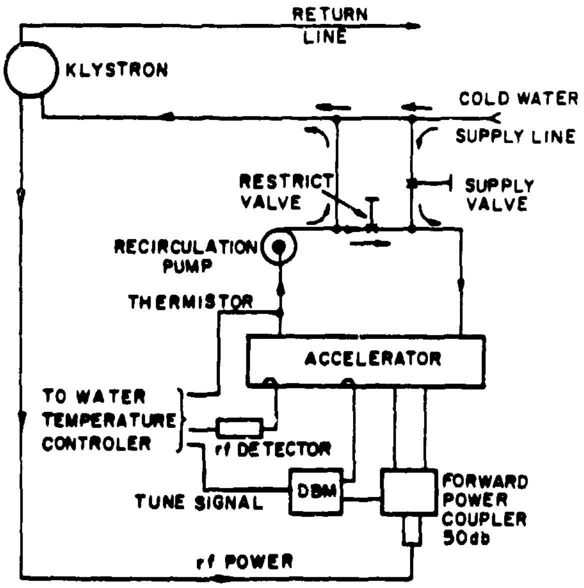

Fig. 2. A typical recirculating-water cooling system used with the resonance-control system.

system. The pump serves as the heat source for heating the water. In this condition, heat is being transferred into the structure. Therefore, the temperature of the circulating water must be above the normal temperature. The temperature of the circulating water is measured using a linear thermistor attached to the copper tubing of the return-water manifold. The resonance controller will regulate the water temperature based upon an operator-adjustable set point and the measured water temperature.

In Zone 2, the resonance error is the dominant process control input. A double-balanced mixer (DBM) is used to sense the resonance condition, and this signal is coupled into the summer circuitry. A sample of the cavity field and the excitation signal are compared in a DBM. The output of the DBM is dependent upon the amplitudes of both inputs and the phase angle between them. The excitation signal sample is derived from the forward power with a directional coupler in the rf waveguide powering the structure. The cavity-field sample is derived from the probe inserted into the cavity. In the off-resonance condition, the DBM output is driven by two terms, a phase-angle term and an amplitude term. Thus, the DBM becomes a sensitive device for measuring the state of the resonance at intermediate- and high-power levels but provides no information when the rf is off or very low.

At high power levels, the temperature of the cooling water can be considerably colder than the temperature set point, which is adjusted for low power operation. To prevent the temperature error signal from driving the cavity off resonance, the field strength within the structure is sampled using a low-barrier Schottky diode (LBSD) detector operating in the linear region. The square of this signal is proportional to the cavity power level. This cavity power signal is inversely combined with the temperature set point. The effect is that as the power in the structure is increased, the temperature set point is reduced. This allows the DBM output to remain near zero when the cavity is on resonance.

The side-coupled structure is water-cooled. The internal cells are water-cooled using many short parallel paths of relatively small dimensions. These channels are machined into the copper disks as a part of the shaping operation and increase the surface area for the circulating water. The supply and return manifolds are plumbed so that the flow direction through the structure alternates on adjacent paths. These techniques are used to minimize any thermal gradients so that the structure operates at a uniform temperature. The circulation system is configured as a low-mass, high-velocity loop, with 0 to 100% recirculation capability. The low-mass objective is necessary for fast response and should be a primary consideration during the design and installation of the manifolds and pumping station. Constant velocity is necessary to ensure that the structure is continually and adequately cooled and can be realized by equalizing the head losses for the recirculation and full-cooling cases.

The Start-Up Process

The start-up process occurs when the power level in the structures makes the transition from zero to maximum power. This transition may be fast, microseconds for pulsed structures, or reasonably slow, a few minutes for cw structures. The start-up process is a difficult task with any one-to-one accelerator system of rf sources and cavities. It is further complicated when a one-to-one correspondence does not exist, neither with multiple rf generators on a single cavity nor with multiple cavities on a single generator. Normally, the cavities are cold at the start of this process because the system has not been running or because it has been running with the rf turned off for some reason. If it has been running at high power, the values are adjusted for the appropriate amount of cooling. The sudden loss of heating from the rf causes the structure to quickly cool down before the controller can readjust the valves to the new conditions.

Because the cavities are normally cold at the start-up, a variable-frequency rf source is used during the start-up process. The frequency is adjusted for minimum total reflected power from all the structures; then the power is slowly increased in all the structures, and simultaneously the frequency is ramped to the normal operating frequency. This process is controlled by an rf start-up program in one of the control-system computers. This start-up process normally takes about three minutes from rf off to rf fully on when the structures are fully conditioned.

Theory of Operation

The temperature control chassis can be subdivided into six major sections. These sections are input signal processing, summation, relay ladder logic, stable voltage reference, process controller, and valve position readouts.

Input Signal Processing

There are four modules, see Fig. 1, within the input-signal processing section. These modules convert the input signals from the temperature set point, structure temperature, structure field amplitude, and the resonance error signals.

Temperature Set Point. The temperature set-point function is implemented with an Action Industries, Inc., AP 4402-267S Module, A5. This module is a two-input summing module. The transfer function is

$$V_0 = K(A + B) ,$$

where A and B are input with a range of 0 to 2 V, K is the gain (nominally 2.5) with adjustable zero and span, and V_0 is the output voltage with a 5-V maximum. The A-input is used to convert the front panel's 10-turn potentiometer voltage into the equivalent of temperature (°F). The B-input is used to provide a bias value (40°F) for the potentiometer input. The span of the manual control is set for 100°F. The gain K is adjusted to provide 15 mV/°F. This allows the temperature set point to be adjusted from 40°F to 140°F.

Structure Temperature. The structure temperature is measured with a surface-mount linear thermistor attached to the return-water distribution manifold. The thermistor output is converted to a temperature value with a Rochester Instruments Systems XSC-1354 Subtractor Module, A4. The transfer function of this module is

$$V_0 = G(K_1A - K_2B) + K_0 ,$$

where A and B are inputs with a range of 0 to 2 V, K_1 and K_2 are gains adjustable from 0 to 1.0, G is the output gain adjustable from 0.5 to 2.5, K_0 is the output offset adjustable from 0 to 4 V, and V_0 is the output voltage with a 5-V maximum. The A-input is used to provide a bias value and the B-input converts the thermistor voltage to a temperature value. The bias value is required to compensate for an offset zero value in the thermistor, and to provide a fail-safe mode where maximum cooling occurs if the thermistor circuit fails. The gain, set to 2.5, within the module is used to scale the temperature to 15 mV/°F.

Power Compensation. A pickup loop senses the rf field amplitude within the cavity. The output of the pick-up loop is connected to a positive-output square-law crystal detector, Hewlett Packard 8470 series or equivalent, by way of an attenuator as required. The rf-power-level signal conditioning is performed in a Rochester Instruments Systems SC-1352 Multiplier/Divider, A1. The transfer function for the module is

$$V_0 = KA_2 ,$$

where A is the input with a range 0 to 2 V, K is the output gain adjustable from 0.5 to 2.5, and V_0 is the output voltage with a 5-V maximum. A voltage divider network restricts the input to the module to less than 1 V at the maximum structure field level. The gain setting required is heavily dependent upon the structure characteristics and must be selected under operating conditions. With the input to the module of 0.5 V at maximum power in the structure, there is a more than 40°F of temperature setback available.

Phase Error. The phase-error signal is processed using a Rochester Instruments Systems SC-1398 Scale and Bias Module, A2. The transfer function of the module is

$$V_0 = K(A - a_0) + d ,$$

where A is the input with a range of ±0.5 V bipolar, a_0 is the input offset adjustable to ±0.5 V bipolar, K is the output gain adjustable from 0.5 to 5, and d is the output offset adjustable from 0 to 5 V.

The phase-error signal is derived from an external DBM. The DBM output must be terminated into 50 Ω to function properly, and the termination is supplied within the chassis. The output level is dependent upon the DBM selected and the amplitude of the input signals. This module expects to receive a 2- to 5-mV/° signal at the nominal operating level of the structure in the zero degree phase-shift region. With the gain set to 2.5, the resultant sensitivity is a 1° phase error, approximately equivalent to a 1°F signal at the nominal operating level of the structure.

Summation. The process control inputs are combined in a Rochester Instrument Systems XSC-1354 Module, A3. The transfer function of the Module is

$$V_0 = K(-K_1A + K_2B + K_3C + K_4D) ,$$

where A, B, C, and D are inputs with a range of 0 to 2 V, K_1 through K_4 are input gains adjustable from 0 to 1.0, K is the output gain adjustable from 0.5 to 2.5, and V_0 is the output with a range of 0 to 10 V.

The manual set point signal is connected to the A-input. The phase-error signal is connected to the B-input. The power compensation signal is connected to the C-input. The structure temperature signal is connected to the D-input. The four inputs are linearly summed, with individually adjustable input gains, into a common output signal. The output signal has separate gain and offset controls.

Process Controller

The process controller is a Honeywell, Inc., UDC 500 Universal Digital Controller with dual output control. The output is configured for proportional and derivative control with time proportioning. Time proportioning cycles the heating or cooling relay on and off with the ratio of on time to total cycle time proportional to the difference of the output of the control algorithm and 50%. The cooling relay is active when the output of the control algorithm is greater than 50%, and the heating relay is active when the output of the control algorithm is less than 50%. The proportional and differential (PD) algorithm in the controller is used to implement an overall proportional, integral, and differential (PID) control loop. The integral function is supplied by the motorized valves, which retain their position until commanded to move. The process controller develops an internal error signal derived by comparing the input signal with an adjustable set-point value. This error signal is used to determine which output is active and the length of time the output is on, thereby determining the direction and the amount of valve motion. Independent gains are provided for the proportional and derivative terms. The control algorithm is implemented using a microprocessor with nonvolatile storage to save the setup parameters.

Relay Ladder Logic

Relay logic is used to steer the process-controller heat and cool commands to the valve actuators and to provide the safety interlocks. Increased cooling is obtained by opening the SUPPLY valve with the RESTRICT valve fully open. When the SUPPLY valve becomes fully open, then more cooling is obtained by closing the RESTRICT valve. Maximum cooling is obtained when the SUPPLY valve is fully open and the RESTRICT valve is fully closed. The heating case operates in reverse. A latching relay circuit, K5, is used to fully open the RESTRICT valve when power is applied to the chassis.

Manual/Automatic Operation

The manual mode of operation disables the output of the process controller and allows the operator to use the spring-loaded toggle switches to command the valve positioners. This option should be used with caution when the rf power is applied to the structure as it is possible to restrict the water flow through the structure.

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